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MECHANISM OF EXPLOSIONS OCCURRING IN DISCHARGE CIRCUITS OF AIR COMPRESSORS

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FRENCH REPORT ON MECHANISM OF THE EXPLOSIONS OCCURRING IN THE DISCHARGE CIRCUITS OF AIR COMPRESSORS

/Following is a translation of the French-language brochure Mecanisme des explosions survenues dans les circuits de refoulement des compresseurs d'air (Mechanism of the Explosions Occurring in the Discharge Circuits of Air Compressors), Technical Memorandum 3/52, April 1952, pages 1-23. The author is R. Loison./

Table of Contents — Page

		Page
I.	Introduction	1
II.	The Behavior of a Deposit of Oil in Contact with an Air Current	3
III.	Observation of an Operating Compressor	7
IV.	Propagation of an Explosion in a Compressed Air Conduit	11
V.	Conclusion	20
VI.	Figure Appendix	23

As a result of the two serious accidents, one at Courrieres on 19 April 1948, the other at Bethune on 6 April 1949, and since both were accompanied by an explosion in a compressed air circuit, CERCHAR undertook a study of the different phenomena related to these types of explosions. A partial report has already been the subject of CERCHAR Technical Memorandum 48/7. This report, by Mr. Loison, Chief Engineer of CERCHAR, describes the tests made at the Verneuil Laboratory and proposes an interpretation of the mechanism of this type of explosion.

I. INTRODUCTION

Nature of the Investigated Accidents

The explosion of 19 April 1948 at Station 4-11 at Courrieres, occurred in the compressed-air circuit which penetrates the air intake shaft. Confining ourselves to the observations relative to the explosion only, and excluding its consequences, we note the following facts:

1. In the intake shaft, the 250-mm-in-diameter compressed air canal showed 22 fissures between the depths of 66 meters and 383 meters. Outside, the line joining the compressor building to the head of the intake (about 7 m long), was blown away by the shock of the explosion.
2. The Dujardin C. V. B. 6, compressor, one of seven, shows traces of a fire. Immediately after the explosion, flames were observed emerging from the safety valves under the exhaust piping. The exhaust valves of the high pressure stage are dirty: their exterior is covered by a coke deposit several millimeters thick. The bottom of the valve chamber is covered by a solid asphaltic deposit more than 5 cm thick. Even the interior of the exhaust piping is coated with a lighter deposit of soot or coal about 5 mm. thick. The reservoir into which this piping leads is covered with a light deposit of light coke.
3. The explosion occurred about 20 minutes after extraction had stopped due to a lack of empty cars.

The accident of 6 April 1949 at Bethune (pit No. 2) is practically analogous to the previously mentioned one:

1. In the shaft, the compressed air piping underwent eight irregularly spaced fissures between the depths of 6 meters and 306 meters.
2. Outside, several fissures occurred in the piping (about 90 meters long) which links the reservoir in the compressor room to the shaft.
3. The interior of the reservoir is covered with numerous layers of coke. A dull, grey, dry deposit partly covers the line which links the reservoir to the Sauter-Harley No. 2 compressor; it is particularly abundant near this compressor. On the other hand, the piping of the other compressors is covered with a greasy deposit 2 to 3 mm thick.
4. In the Sauter-Harley No. 2 compressor, the exhaust valves of one of the cylinders are much drier than the rest and present a

characteristic dull greyish finish. This compressor had a much higher than average oil consumption (280 kg per month, compared to 50 kg per month). Since this compressor was used to meet peak demands, the high oil consumption was no doubt due to frequent vacuum operating conditions: vacuum operating conditions which are obtained by closing the intake, tend to create subatmospheric pressures in the compressor, and thus cause the rising of oil from the crank case into the lower part of the cylinder. This compressor was in good working order. The temperature of the compressed air, measured after the accident, after dismantling and reassembly, was found equal to 120 degrees.

Outside of these two serious accidents, numerous compressor incidents have been observed for a long time. These incidents consisted of either a local heating of a certain pipe or reservoir, or an explosion whose extension, in general, was very limited. It is probable that the starting mechanism of the phenomenon is the same in all cases: the two accidents at Courrieres and Bethune are conspicuous because of the abnormally large extent of the explosion.

Phenomena Studied

The combustible elements which are the origin of the observed explosions can only come from the lubricating oil of the compressors; this oil, partially entrained by the compressed air, is deposited in the reservoir and the piping. Thus we were brought to studying, in the laboratory, the action of an air current on an oil deposit. We ascertained that under certain conditions this deposit on the one hand may become over-heated, and on the other hand may be the source of combustible vapors which may spontaneously ignite.

Through observations over a long period of time of the compressor installation at Courrieres, we subsequently determined these practical operating conditions. A comparison of these conditions with laboratory results enabled us to explain the origin of the fire flashes and the explosions of limited extent which are observed from time to time in compressor installations.

However, the Bethune and Courrieres accidents present a different problem. In fact, in both cases the conduit was broken at several points along a length of more than 300 meters. Each fissure is the origin of an expansion wave which is propagated with the speed of sound through the conduit when the pressure is brought to atmospheric. The fact that there were several fissures shows that a pressure wave travelled through the conduit at a speed superior to the speed of sound. In other words, a detonating condition was established in the conduit. New experiments, performed under conditions approaching reality, showed that a detonating condition could effectively be established in a conduit whose interior wall is covered with a deposit of oil.

II. THE BEHAVIOR OF A DEPOSIT OF OIL IN CONTACT WITH AN AIR CURRENT

The possible resultant reactions of the contact of an air current with an oil deposit depend essentially on the form and support of the deposit, its position in the air current, and the velocity of the air current. In fact, these different factors intervene in two ways:

--on the one hand, like all reactions between solids and gases, the speed of reaction depends on the facility with which the oxygen of the air can reach the surface of the deposit;

--on the other hand, since some of these reactions are exothermic, the temperature of the deposit may be raised and the speed of reaction accelerated. The temperature increase depends on the conditions of heat removal by conduction, radiation, and convection.

We used two types of apparatus successively: the first was more favorable for reproducing the phenomena to be studied, the second was closer to reality.

First Experimental Apparatus

A flow of oxygen at atmospheric pressure, raised to temperature T_1, travels through an oil impregnated mass which is placed in an enclosure maintained at the same temperature T_1. The apparatus is shown in detail in Figure 1.

When the temperature T_1 is below a certain limit, which we will designate critical temperature θ_i, the oil undergoes a slow oxidation, and its temperature remains constant and equal to that of the incident air flow. The higher temperature T_1 is, the greater will be the speed of oxidation; the speed of oxidation varies greatly with the nature of the support: with grains of ferric hydrate it is appreciable at a relatively low temperature, of the order of 60 to 80° C.

When the oxygen temperature T_1 increases beyond the critical value θ_i, the temperature of the support increases constantly above T_1, and as a result of the condensation of the vapors due to the decomposition of the oil, white fumes are observed downstream of the oil deposit. Their concentration increases and they spontaneously ignite, resulting in a steady flame being established downstream of the oil deposit.

The critical temperature θ_i is naturally dependent on the parameters which define the operating conditions. We recorded the following values:

150 degrees--with a flow of oxygen at a speed of 1 cm/sec through a 30-mm-in-diameter horizontal tube which, over a length of 20 mm and full cross section, contained 0.3 mm ferric hydrate grains impregnated with 15% by weight of D 15 virgin oil;

160 degrees--with the ferric hydrate grains replaced by grains of rust;

180 degrees--without catalyst, with the use of deposits collected from the two exhaust valves of the Courrieres compressor;

300 degrees--with the use of virgin D 15 oil deposited on silica grains.

Thus it was established that the passage of a flow of oxygen at atmospheric pressure through a mass of rust impregnated with compressor oil, may, if its temperature reaches a value of the order of 150 to 160 degrees:

--raise the temperature of the oil deposit to a level which is definitely higher than that of the oxygen flow;

--or create combustible vapors; when their concentration reaches a sufficiently high level, they ignite. Their ignition may be caused by the support of the deposit.

Obviously, the first phenomenon is due to an exothermic oxidation reaction; it occurs when the quantity of heat given off is such that it cannot be entirely removed by the convection of the gas flow.

The second phenomenon is probably the result of cracking reactions which create products lighter than oil; it occurs when the temperature of the oil deposit is sufficiently elevated by its own oxidation. The mechanism of these reactions is not unknown to us and the experiments were not made with the objective of its determination.

The operating conditions of this first series of tests differ notably from reality.

In particular:

1) A flow of oxygen at atmospheric pressure was used. As a first approximation, we may estimate that the phenomena in air are determined by the partial pressure of oxygen, and that an analagous result would have been obtained with air at a pressure of 5 kg, a pressure close to and even a little below that in a compressed air conduit not far from the compressor. However, this approximation is not exact, because of the calorific capacity of nitrogen.

2) The apparatus is favorable to an increase in the temperature of the oil deposit. In fact, the deposit is plunged into the gaseous flow, and can hardly give off heat by any other means except convection; heat transfer by conduction being negligible.

Second Experimental Apparatus

A flow of air, at an affective pressure of 7 kg, raised to a temperature T_1, travels through an oil-impregnated mass placed in an enclosure which is maintained at the same temperature T_1. The details of the operating procedure are shown in Figure 2.

This apparatus differs from the first in that it uses air instead of oxygen and also because of the possibility of much greater gaseous flows. It is possible to reach air flow speeds of 5 meters per second, which is the order of magnitude of speeds attained in practice.

Each test consists of progressively raising the temperature of the oil deposit at the average rate of 1.5 degrees per minute. The temperature of air (T_1), and the temperature of the mass supporting the oil deposit (T_2) are measured within one degree. Also, the difference $T_1 - T_2$, is measured directly by means of two opposing couples T'_1 and T'_2. Regular analyses of the air that has travelled through the deposit are made. Qualitatively, the phenomenon is analagous to that observed by means of the first apparatus.

1) Heating the oil deposit. The curves of temperature recorded during a test are of the type indicated in Figure 3.

The temperature θ_c, above which T_2 becomes superior to T_1, corresponds to the development of an exothermic reaction. It will be called in abbreviated form "the oxidation threshold"; this does not mean that oxidation really starts only at temperature θ_c, but that it is hidden at lower temperatures because of the lack of sonsitivity of our measuring apparatuses and by the transfer of heat by convection, which tends to equalize T_1 and T_2.

When the velocity of air flow is high (2 to 5 meters/sec) no gap appears between T_1 and T_2, obviously because convection, very important at these speeds, completely masks the discharge of heat from the oxidation reactions.

The oxidation threshold, θ_c, is very apparent at lower speeds. The following values were observed:

Nature of the deposit	Velocity of air flow	Oxidation threshold
11% D15 oil on rust	2 cm/sec	202°
"	12.5 cm/sec	172°
15% D15 oil on ferric hydrate	2 cm/sec	158-160°
"	12.5 cm/sec	137-140-145-162-175°
Deposit collected in the valve chambers at Courrieres	12.5 cm/sec	154°

The lowest oxidation threshold, about 140 degrees, was obtained at a speed of 12.5 cm/sec with ferric hydrate. On the average, the oxidation threshold is lower with the use of ferric hydrate than with the use of rust. It is lower at a speed of 12.5 cm per second than with a speed of 2 cm/sec. Moreover, since it is not perceptible for very high speeds, it must be concluded that it attains a minimum for a certain air flow speed.

2) Ignition. The ignition of the gas after passing through the oil deposit was observed under diverse conditions.

a) With the air flow constant, ignition is spontaneous as soon as the temperature of the air flow T_1 reaches a certain limit θ_i.

b) The air flow temperature, having reached a certain value T_1 without any observed ignition, the flow is suddenly stopped. An ignition is immediately produced if T_1 is higher than a certain limit θ_c.

c) The air flow temperature having reached a certain value T_1 without any observed ignition, the flow is suddenly stopped. The temperature of the deposit increases rapidly. Then flow is re-established; ignition occurs immediately after, provided that T_1 is higher than a certain limit θ_3. The table below condenses the data obtained (the values of θ_2 are only higher limits determined by trial and error).

Nature of the deposit	Speed of air flow	Ignition temperature		
		Operation a)	Operation b)	Operation c)
11.5% D15 oil on rust	2 cm/sec	-	237°	-
"	12.5 cm/sec	-	228°	207°
"	500 cm/sec	$>250^\circ$	250-204°	-
15% D15 oil on ferric hydrate	2 cm/sec	170-180°	-	-
"	12.5 cm/sec	187-197°	222°	155-157°
"	500 cm/sec	$>250^\circ$	206-223°	-

An examination of this table evokes the following comments:

1) With a high and uninterrupted flow we were unable to observe any ignition (following procedure a)) despite the fact that a temperature of 250° was reached. This is probably because the vapors produced by the cracking of the oil became diluted by the air flow such that the lower ignition point cannot be reached. However, if the flow is stopped, ignition is observed at temperatures in the neighborhood of 200° (procedure b)).

2) With an uninterrupted flow, the ignition point is lowered as the flow is decreased.

3) The operating conditions which bring about the lowest ignition temperature are those which consist in stopping the flow a short time after oxidation begins and re-establishing it immediately after (an interruption of less than one minute). With these conditions, ignition was obtained between 151 degrees and 157 degrees with oil-soaked ferric hydrate.

These observations are in agreement with the nechanism already described in the previous paragraph. In order that ignition be obtained, two conditions are necessary:

1) The temperature of the oil deposit must be high enough for cracking reactions to develop and thus produce combustible vapors. For a given air-flow temperature, the greater the speed of reaction and the less heat released by the deposit, the higher the oil-deposit temperature will be. Since an increase in air flow increases both the speed of reaction and the quantity of heat removed by convection simultaneously, we can see that the oil-deposit temperature will have a maximum for a certain value of the air flow.

2) The concentration of combustible vapors in the air must reach the lower limit of ignition; for a given oil-deposit temperature, this concentration varies inversely with the air flow. When the oil-deposit temperature has reached a sufficiently high level to allow the decomposition of the deposit, a reduction in flow—better still, a sudden stopping of the flow—provokes the formation of an inflammable gaseous mixture.

The operating conditions realized by this second experimental apparatus are still quite different from the practice by the fact that the air flow travels through the oil deposit, while in a conduit or reservoir the oil deposit covers only the inner walls. Thus if our experiments enable us to obtain an idea of the mechanism which creates the ignition, the limit ignition temperature obtained from these tests cannot be applied in practice without precautions. We may think that our operating conditions are more severe than those in the practice because, on the one hand, the heat released by the oxidation of the oil can be transferred only by convection and not by conduction, which favors an increase in temperature. And because, on the other hand, the contact area between the oil deposit and the air is large, and this is conducive to a high concentration of combustible vapors. Inversely, however, we have not exhausted all the imaginable methods of operation. Notably, it is possible that certain laws of variation of flow as a function of time, or that certain oil deposits having aged under particular conditions, are conducive to lower ignition temperatures. Thus it seems wise to consider 150 degrees as the limiting temperature above which ignition is possible.

III. OBSERVATION OF AN OPERATING COMPRESSOR

From October 1949 to January 1951, in liaison with the Nord Pas-de-Calais coalbasin, we observed the operation of a compressor identical to that of Station 4 at Courrieres (Dujardin c.v.D.6, 400 ch.), but located in the neighboring pit.

A. Measuring Apparatuses

The measurements consisted in recording the flow, the pressure, and temperature at different points in the air circuit, from the intake of the low-pressure cylinder to the discharge of the high-pressure cylinder.

The pressure taps P_0, P_1, P_2, P_3, P_4, and the location of the thermoelectric couples C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, are shown in Figure 4. Pressure and flow measurements, for which no particular accuracy was required, were made by means of standard instruments (Brown-type recorders). However, the temperature measurements deserve some comment.

Chromel-alumel thermoelectric couples were used and installed as indicated in Figure 5:

Diagram A: "Typical couple detail."

Diagram B: "Installation on a cylinder enabling temperature measurements near a valve."

Diagram C: "Installation on a conduit enabling temperature measurements at its center."

These installations permit temperature measurements at a precise point. Moreover, the perforated copper tube which encircles the cable sheath shields the cable from radiation from the walls while allowing a flow of gas around the couple. The very limited importance of radiation at the temperatures in which we are interested makes superfluous the use of a more accurate but more complicated instrument, such as a pyrometer.

The signals from the thermocouples are relayed to an eight-branch potentiometer with automatic cold solder compensation. The connections from the couples to the recorders are entirely made of compensating wire, thus providing an accuracy of the order of one degree.

The manufacturer furnished the compressor with three thermometers: T_1, T_2, T_3, located respectively on the exhaust pipe of the high-pressure cylinder, and at the entrance and exit of the refrigerant (see Figure 4). Each one consists of a mercury thermometer placed in contact with the metal wall without regard for any particular pecautions. Thus the readings are inaccurate because of heat transfer by the wall, both by radiation and conduction, and also because the air temperature is higher at the center of the cross section than near the walls. In fact, the thermometers T_1, T_2, and T_3 always registered values lower than those indicated by the couples close to them. The difference reached 28 degrees in the exhaust pipe (couple C_7 and thermometer T_1).

TABLE I

Dates		Temperatures °/C												Effective Pressures k_2cm^2				
Day	Hour	Intake Pipe Couple 1	Entrance of Intake Valve, Low Pressure, Couple 2	Exit of Exhaust Valve, Low Pressure, Couple 3	Exit of Refrigerant Couple 4	Entrance of Intake Valve, High Pressure, Couple 5	Exit of Exhaust Valve, High Pressure, Couple 6	High Pressure Exhaust Piping Couple 7	Diaphragm Couple 8	High Pressure Exhause Piping Thermometer T_1	High Pressure Exhaust Piping Thermometer T_4	Low Pressure Exhaust Piping Thermometer T_2	Exit of Refrigerant Thermometer T_3	Low Pressure Intake P_o	Low Pressure Exhaust P_1	High Pressure Intake P_2	High Pressure Exhaust P_3	Diaphragm P_4
30-3-50	18:30		35	152	59	62	142	142	135	114	140	131	45	0	1.95	1.6	5.6	5.6
31-3-50	2:30		-	153	-	-	146	-	-	-	-	-	-	-	-	-	6	-
	5:45		-	150	-	-	143	-	-	-	-	-	-	-	-	-	5.9	-
	9:20		30	145	57	58	127	127	122	-	-	-	-	0	2	1.6	5.0	5.0
	10:45		35	150	59	59	140	140	132	114	139	130	44	0	2	1.7	5.8	5.8
	13:10		37	152	61	63	141	141	132	-	-	-	-	0.1	2	1.7	5.8	5.8
	13:25		57	134	64	90	123	106	95	vacuum operation		-	-	-0.8	0.75	0	+5.1	-
	13:45		38	151	57	60	152	-	132	-	-	-	-	0	2.05	1.8	7.2	7.3
	13:55		-	154	62	62	160	160	-	-	-	-	-	0	2.05	1.8	7.2	7.3
22-29-4			35	150	57	60	134				135	130		0.1	1.95	1.8	5.7	5.7

Average Temperatures

B. Temperature Variations in the Course of One Day

The temperature of the exhaust air is subject to oscillations which are due to reservoir pressure variations which, in turn, are due to the changing compressed-air requirement. Table 1 gives an example of these variations. The difference between the extreme values of the high-pressure exhaust never exceeded 10 degrees for pressure variations of less than 0.35 kg (that is, 7%).

Moreover, the "vacuum operation" phases are marked by sudden and ephemeral temperature variations, which are very characteristic (Figure 6). Vacuum operating conditions are generally obtained (and this holds for the observed compressor) by closure of the low-pressure intake by means of a relay valve which operates as soon as the general exhaust pressure reaches a certain value; the low-pressure cylinder is then at a pressure lower than atmospheric, the high-pressure cylinder reverts to atmospheric pressure by means of an equilibrium valve controlled by the pressure in the low-pressure cylinder.

At the very beginning of negative gauge pressure operation, the exhaust air temperature (high pressure as well as low pressure) decreases suddenly at first and then more slowly. However, the intake air temperature (high pressure and low pressure) increases; increases of from 20 degrees to 40 degrees have been observed.

When negative gauge pressure operation ceases, the intake temperature decreases and rapidly reaches the value it had prior to vacuum operation. The exhaust temperature increases very rapidly and attains for a hort period of time a value exceeding that which it had prior to vacuum operation, and then progressively tends toward its initial value. The observed increase in temperature may be of the order of ten to fifteen degrees C.

The explanation of this phenomenon seems to be the following: during so-called vacuum operation, the air no longer flows uniformly from the intake to the exhaust. Rather, it is stirred up or buffeted around inside the cylinders, which tends to decrease the temperature gap between the intake end and exhaust end of the compressor. This explains the raising of the temperature at the intake end. When the compressor is put back into operation, the air taken in is raised by the walls of the compressor to a temperature which is higher than its normal value; the quasi-adiabatic compression to which the air is subjected thus also raises its exhaust temperature to a higher value than its normal exhaust temperature.

C. Temperature Variations Over a Long Period

Initially (in October 1949) the cylinders and valves were perfectly clean. However, according to the engineers in charge of its maintenance, the flow of refrigeration water was insufficient.

At the low-pressure exhaust (couple No. 3), an average temperature of 145 degrees was recorded with rare peaks at 155 degrees; and at the high pressure exhaust, an average temperature of 131 degrees, with a few peaks at 143 degrees. The average effective pressure was 5.5 kg.

During the month of April 1950, these temperatures progressively increased; by the end of April they had reached an average of 155 degrees at the low-pressure end and 145 degrees at the high-pressure end. Peaks in excess of 150 degrees were frequently observed at the high-pressure end; in particular, the temperature remained at 153 degrees for one hour and fifteen minutes, while during the same period the temperature at the low-pressure end established itself at 159 degrees.

A complete overhaul of the compressor and a cleaning of the refrigerant were made in May 1950. After this the average temperatures fell back to 120 degrees at the high-pressure exhaust and 140 degrees at the low-pressure exhaust. They were still of the same order in January 1951.

A few tests during which the effective pressure at the exhaust was raised to 7 kg, brought about temperatures of 154 and 160 degrees at the low-pressure and high-pressure exhausts respectively, during a period when the observed temperatures at a pressure of 5.5 kg were 140 degrees respectively.

D. Analysis of the Deposit Collected in the Exhaust Piping

A sample of the deposit covering the interior surface of the exhaust piping (at 2.50 meters from the compressor) was subjected to a fractionated dissolution, the solid residue being subsequently incinerated. The following result was obtained:

--35% soluble in standard hexane; these consist of unadulterated oils;

--6.5% insoluble in hexane but soluble in benzene; these resemble asphaltines which result from the partial oxidation of oil;

--37.7% insoluble in both hexane and benzene; after transformation to gaseous products by incineration, these consist of organic matter which is the result of an adulteration of the oil and, eventually, of combustible dusts;

--the remainder, that is, 20.8%, is a solid residue and incombustible; it consists for the most part of iron oxides (64% ferric oxide, 5.2% silica, and 4% alumina).

Thus these deposits consist of a mixture of dusts, rust, and oil, the greater part of which has been transformed into heavier products.

IV. PROPAGATION OF AN EXPLOSION IN A COMPRESSED AIR CONDUIT

In the last part of this study, it was our intent to investigate the conditions under which an explosion could develop in a conduit which is capable of producing mechanical effects similar to those observed as a result of the Bethune and Courrieres accidents. It must be remembered that the latter were characterized by the rupture of the conduit at several points distributed over a great length, which case requires that a pressure wave be propagated at a speed higher than the speed of sound.

First, we supposed that such a phenomenon could not occur unless the conduit had been previously fitted with an inflammable gaseous mixture; our experiments rapidly demonstrated that under these conditions the mechanical results were effectively of the same order as those which were observed at Courrieres and Bethune.

Later it was suggested that an initial formation of a gaseous mixture in the conduit might not be necessary for the propagation of the explosion, and that the existence of a very thin deposit might suffice. This was ascertained in a new series of experiments.

Moreover, on the day of the accident at Bethune another hypothesis was advanced, viz., that the explosion might have been caused by the detonation of an explosive charge at a short distance from the compressed air conduit. In fact, we observed on the conduit in question deformations whose characteristics could have been explained by this hypothesis. In order to investigate grounds for such an hypothesis, it was assumed that the conduit had been initially filled with an inflammable gaseous mixture.

Finally, we investigated the possibility of stopping an explosion in a conduit by means of a flame-cutting apparatus consisting of a stack of small plates analagous to those used on Diesel locomotives.

All of these experiments were made with compressed-air conduits of a standard type: 250-mm-in-diameter pipe with a 7-mm wall thickness, furnished by the Nord Pas-de-Calais pit.

A. Propagation of an Explosion in a Gaseous Mixture

In the course of the first experiment, a 42-meter-long conduit was filled with the air + methane stoechiometric mixture at a pressure of 7 kg. An electric spark plug placed at one end of the conduit provides for the inflammation of the mixture. The explosion was accompanied by considerable mechanical consequences: the conduit was broken at the welding of the assembly couplings, or was manifested by a large fissure in the wall, with the wall literally cut into lacelike patterns. Certain pieces of piping were thrown over a great distance.

The experiment was repeated several times during the study mentioned in paragraph C, but with air + hydrogen mixtures. Similar mechanical consequences were obtained every time.

Thus it is determined that a detonating flow, or at least one intermediate between a deflagrating flow and a detonating flow, may be established in a mixture of air and methane or hydrogen under pressure. This detonating flow is capable of causing the rupture of a conduit at several points distributed over a certain length.

B. The Propagation of an Explosion in the Absence of a Preliminary Gaseous Mixture

1) Experimental apparatus. A conduit of length L is filled with air at a pressure of 7 kg; its inner surface is covered with a combustible deposit whose nature varies from one test to the next. The conduit is extended by an ignition chamber which consists of a 4-meter-long piece of conduit filled with an inflammable gaseous mixture, at a pressure of 7 kg. The conduit itself and the ignition chamber are separated by a klingerite membrane; they are simultaneously pressurized, thus permitting the use of a very thin membrane which would not withstand the pressure of 6 kg. Ignition is obtained by means of a spark plug. Wires are stretched across the conduit at several points, and connected to electric circuits, thus enabling the recording of the displacement of the pressure wave.

The experiments which were carried out are summarized in Table II.

In tests 1 and 2, the gaseous mixture filling the ignition chamber consisted of the stoechiometric mixture air + methane. For all the other tests, a mixture enriched with oxygen was used (25% O_2, 12.5% CH_4, 63.5% N_2), in order to make the initial cause of ignition more violent.

The oil used to manufacture the deposit was D15 oil, which is customarily used for lubricating the compressors. In tests 6, 7, 8, and 9 it was arranged in elongated nacelles resting on the bottom of the conduit. In tests 2, 3, 10, and 11 it was spread over the entire inner surface of the conduit.

2) Test results. These are briefly summarized in Table II. The table evokes the following comments:

TABLE II

Test No.	Nature of the Deposit	L Meters	Results Obtained
1	No deposit	95	Nothing
2	Oil and lampblack	95	Burning of the deposit over a length of meters. No mechanical consequences.
3	Oil and lampblack	95	Explosion over the entire length. Very violent mechanical consequences.
4	No deposit	35	Nothing
5	No deposit	35	Nothing
6	30 grams of oil per meter	70	Burning of oil along 10 meters. No mechanical consequences.
7	30 grams of oil per meter	70	Burning of oil along 15 meters. Only one conduit fissure, occurring in the neighborhood of the ignition chamber.

8	60 grams of oil per meter	60	Explosion over the entire length. Violent mechanical consequences.
9	60 grams of oil per meter	50	Burning of oil along 15 meters. Only one conduit fisure, occurring in the neighborhood of the ignition chamber.
10	180 grams of oil per meter	50	Explosion over the entire length. Very violent mechanical consequences.
11	180 grams of oil per meter	45	Explosion over the entire length. Very violent mechanical consequences.

1. In the absence of a combustible deposit on the inner surface of the conduit, the mechanical consequences of the explosion of the gaseous mixture which fills the ignition chamber are imperceptible (tests 1, 4, 5). Evidently this result was to be expected, but it seemed necessary to make this verification in order to validate all the other tests.

2. Tests 3, 8, 10, 11 produced the propagation of a flame over the entire length of the conduit. This is a result of two observations:

--On the one hand, the oil deposit disappeared over the entire conduit length to be replaced by a deposit of soot;

--On the other hand, flames were observed at the different points of conduit fissures and especially at the end opposite the ignition chamber. Moreover, the flames were immediately followed by a thick cloud of black smoke consisting of soot.

3. The mechanical damage observed during tests No. 3, 8, 10, and 11 included rupture of the conduit at several points, the blowing away of the bottom, and, in certain cases, the rupture of several parts of the conduit. The diagram of Figure 7 (relative to test No. 3) and the photos of Figures 8, 9, 10, and 11 (relative to tests No. 8 and No. 10) provide an idea of the nature and intensity of the mechanical damage observed. The damage is qualitatively analagous to that observed during the explosion of the gaseous mixture, but more violent.

4. In test No. 3, a deposit of soot was superposed on the oil layer in order to provide conditions which were as dangerous as possible at the very beginning of the series of tests. Later tests showed that it was not necessary to have soot in the conduit to produce a detonation over the entire length of the conduit. In particular, the conduits used in tests 10 and 11 were thoroughly cleaned, prior to the tests, in order to remove any traces of soot from previous tests.

5. In tests 7 and 9, the oil was burned over a limited length only. Also, the conduit was broken at one place only, in the immediate vicinity of the ignition chamber. Because of the expansion caused by the rupture of the conduit, it is possible that this last phenomenon is the cause of the first. It may be observed that in tests 8, 10, and 11, the rupture closest to the ignition chamber is about 15 meters away from it.

In test No. 3, the conduit was broken at seven different points, one of which was in the immediate vicinity of the ignition chamber. However, we may reason that, the combustible deposit being abundant, the effect of an expansion was not sufficient to slow down an already violent combustion.

6. Within the limits of the deposits experimented with, it can be said that the more abundant the deposit, the greater the chances for an explosion of the conduit. It must be noted, however, that a deposit of 180 grams per meter of conduit is still very thin; it corresponds to an average thickness of 3/10 of a millimeter. The 30 g/m deposit corresponds approximately to the stoechiometric mixture of air and oil.

7. When the gaseous mixture of the ignition chamber consisted of an air-methane mixture, no conduit explosion was observed. All the observed explosions occurred with an oxygen-enriched mixture. It is true that this information is based on a single test (test No. 2), but it seems to be well enough established, because the combustible deposit used in this test was identical to that of test No. 3, during which an extremely violent explosion was observed.

The fact that an oxygen-enriched mixture was used in the ignition chamber to start the explosions in the conduit, in no way depreciates the generality of this phenomenon and certainly does not exclude the possibility that an explosion can just as well occur in a real conduit where the air is not enriched with oxygen. In fact, an equally violent explosion could have been obtained by filling the ignition chamber with an inflammable mixture, without the addition of oxygen, provided the ignition chamber was long enough; the experiments described in paragraph A seem sufficient to support this argument. We did not try to verify this experimentally, because an increase in the length of the ignition chamber would have forced us to lengthen proportionately the conduit itself, in order to limit relatively the proportion of conduit subjected to the direct consequences of the explosion of the gaseous mixture and keep an appreciable length of conduit in which the propagation of the combustion of the oil deposit could be observed "in the pure form."

The data on the speed of the pressure wave led to the following observations:

1. In the tests where the conduit exhibited only one fissure near the ignition chamber (tests 7 and 9), at first the speed of the wave (300 to 400 m/sec at the entrance of the conduit) increases rapidly. It reaches a maximum of about 800 to 1,000 m/sec a few meters downstream of the combustion chamber, and then decreases. It is no more than 200 to 400 m/sec at the end of the conduit.

2. In the tests where ruptures were observed at several points on the conduit (tests 8, 10, 11), the wave travelled at a rapidly increasing rate of speed to reach approximately 1,200 m/sec and remained at that speed all the way to the end of the conduit.

These tests prove that, when the initial ignition is violent enough, a pressure and combustion wave can be maintained and propagated at a speed in the neighborhood of 1,200 m/sec in a conduit whose inner surface is covered only by a thin oil deposit and in which there is no pre-existing inflammable gaseous mixture.

3) Interpretation. This phenomenon can be compared to dust explosions. In fact, our operating procedure is definitely analogous to that used in the dust adits of test stations, which is generally the following:

Coal dust is deposited on the wall of an adit. At its end, in an ignition chamber separated from the adit by a simple sheet of paper, an inflammable gaseous mixture is prepared. The explosion of the mixture causes the ignition of the dust which can be propagated along the entire length of the adit.

The mechanism of dust explosions is well known, at least in a general way. The pressure wave caused by the explosion of the gaseous mixture raises the dust from the walls of the adit, thus creating a cloud through which the flame can be propagated. The flame, in turn, is the origin of a pressure wave preceeding it so that there is always a cloud of raised dust before it, thus enabling its propagation in the same way as a flame in a gaseous medium.

However, the transposition of this explanation to the case before us cannot be made without some caution.

In fact, we must imagine how the passage of a pressure wave can generate, behind it, an inflammable mixture in which the flame can travel.

The consecutive air flows, due to the passage of the pressure wave, are definitely incapable of creating a suspension of oil from a thin film of a few tenths of a millimeter deposited on the inner surface of a conduit. However, the passage of the wave is accompanied by an increase in temperature which may bring about the vaporization of the oil. The more violent the wave, the more impressive will be the increase in temperature. It is only 66 degrees for a wave travelling at 460 m/sec. (The ratio of wave front pressure to initial pressure is equal to 2.) It reaches 467 degrees for a wave travelling at 1,000 m/sec. (The ratio of wave front pressure to initial pressure is equal to 10.) At this temperature the vaporization of oil must be rapid; moreover, the oil vapors are capable of spontaneous ignition. Thus it is probable that the propagation of the combustion of the oil is not from one point to the next, each portion igniting the next by conduction, radiation, or diffusion, as in a gaseous deflagration or a dust explosion, but rather like a detonation in a gaseous medium caused by an increase in temperature due to the passage of the shock wave. However, this mechanism differs from a detonation in a gaseous medium in that, in this case, the temperature increase performs two functions: first, instigating the vaporization of the oil, and then igniting the oil vapors.

At first glance it seems surprising that the vaporization of the oil proceeds so rapidly that it can feed a flame travelling at such a high rate of speed. In this respect, we can make the two following remarks:

—on the one hand, since the vaporization of the oil is immediately followed by its ignition, the temperature of the deposit increases rapidly above that caused by the passage of the shock wave; we can conceive that vaporization will proceed extremely rapidly.

--on the other hand, it is not essential to suppose that the flame front is very near the pressure wave front (for the detonation of a gaseous mixture, these two fronts coincide): the successive pressure increases, and the ensuing ignition of new layers of combustible material are capable of maintaining a shock wave, even if it is located a certain distance forward. Thus a certain delay may elapse between the passage of the pressure wave and ignition, which also may be progressive.

The starting of the explosion in the conduit no doubt causes the interference of other phenomena. In fact, the speed of the shock wave generated by the explosion of the gaseous mixture in the ignition chamber is only 400 m/sec. The resultant increase in temperature (60°) seems insufficient to induce a rapid vaporization of the oil. However, the increase in temperature due to the contact of the hot smoke produced by the explosion is definitely added to the above-mentioned increase.

C. Detonation of an Explosive in the Vicinity of a Conduit Filled With An Inflammable Gaseous Mixture

1) Operating procedure. The experimental apparatus is the following: a 40-meter-long conduit, closed at both ends, is filled with a gaseous mixture compressed to a pressure of 7 kg and consisting, for most of the tests, of a mixture of hydrogen and air with 30% hydrogen. The first tests, made with the stoechiometric air + methane mixture, yielded no positive results; thus we thought of increasing the severity of the tests by substituting hydrogen for methane.

An explosive charge is set off in the vicinity of the conduit. The weight of this charge and its distance from the conduit were chosen in such a way as to produce on the conduit a dent 60 to 80 cm long and 10 to 12 cm deep (that is, 1.2 to 1.5 kg of dynamite-gum 10 cm from the conduit).

2) Test results. The effect of the charge varied from one test to the next, due to the unequal resistance of the different pipes. Some tests yielded dents which were extremely difficult to perceive, while others caused the breaking of the pipes in the immediate vicinity of the charge. Thus a large number of tests are insignificant.

Table III summarizes the tests in which the dent on the conduit was very conspicuous. Explosion of the gaseous mixture trapped in the conduit did not occur in any of the other tests.

TABLE III

Test No.	Length of conduit (m)	Weight of explosive charge (kg)	Distance of the explosive charge (cm)	Action of blasting on conduit	Test results
1	42	1.500	15	Dent: 0.62 x 0.21 x 0.15	No ignition
2	35	"	6	Dent: 0.38 x 0.21 x 0.15	No ignition
3	42	"	10	Dent: 0.40 x 0.20 x 0.10	Ignition
4	42	"	8	Dent: 0.61 x 0.20 x 0.14 At the bottom of the dent, a fissure 1 mm wide by 20 mm long.	Ignition
5	42	"	15	0.40-meter-long tear in the conduit facing the explosion	Ignition
6	35	"	10	25-cm-wide by 52-cm-long tear in the conduit.	Ignition
7	21	"	8	Dent: 0.60 x 0.20. Transverse break in front of the charge over 3/4 of the circumference	Ignition

The ignitions observed during tests 4, 5, 6, and 7, in which the conduit was opened up by the blast of the explosives, are easily explained and provide no new information. Only the first three tests are of interest. Only one of them, test No. 3, led to the explosion of the conduit.

This result seems very strange to us. We have no cause to doubt it, but we were unable to repeat it. A total of twenty tests were made, of which only a small number are significant for the reasons outlined above.

It would be unwise to build an elaborate theory to explain this unique ignition. One might think of ignition by shock wave, but the shock wave generated by the detonation of the explosion must be singularly attenuated by its passage through the conduit. The most probable hypothesis seems to be the following: due to the detonation of the explosive, the conduit is subjected to a very sudden deformation; this is accompanied by a temporary, and probably very local, increase in temperature, but one sufficient to ignite the gaseous mixture. We do not know the temperature which the inner surface of the conduit must reach to cause ignition of the stoechiometric mixture hydrogen + air at a pressure of 7 kg. In a uniformly heated enclosure, the ignition temperature of hydrogen under a pressure of 7 kg is of the order of 460°, however, in the case of localized heating of the wall, the temperature is certainly higher. Moreover, we have no idea of the temperature which the wall may attain when subjected to a sudden deformation; thus this explanation is afforded with all possible reservations.

We did not pursue this experiment, as it assumes that the conduit is filled with an inflammable gaseous mixture prior to the test, a condition that is very difficult to admit in reality. Moreover, the experiments described in paragraph B, which were undertaken in the meantime, showed that this hypothesis was unnecessary.

D. Flame-Cutter Tests

At our direction, the Nord Pas-de-Calais establishment constructed a flame-cutter consisting of a stack of 58 annular plates (internal diameter 270 mm, external diameter 670 mm) 3 mm thick, and spaced at 0.5 mm (Figure 12). It was inserted between a 35-m conduit section and a 7-m section. Having filled the conduit assembly with an air-methane stoechiometric mixture at a pressure of 7 kg, ignition is effected by means of a spark plug located at the end of the 35-m section. A very violent explosion developed in the conduit, the 35-m section was broken in several places, and its pieces were thrown some distance to the rear. The casing holding the stack of plates was blown from the plates (an action requiring a force of from 800 to 1,000 tons). The 7-meter section, located downstream of the stack of plates, was thrown forward, but the flame did not travel through it. This statement is based on the fact that the cotton-powder wires, stretched across the conduit prior to the test, remained intact.

Thus the flame-cutter proved to be affective. A priori, this result was not obvious, because stacks of plates, and the anti-deflagration joints in general, are always tested with a slow-speed deflagration.

This experiment does not permit us to state with certainty that this flame-cutter would have been capable of preventing the propagation of an explosion such as that experienced at Courrieres and Bethune, for two reasons:

1) It is probable that the explosion propagated itself in a manner analagous to that of the experiments described in paragraph B rather than through a formed gaseous mixture. It is not certain whether the flame-cutter would exhibit the same effectiveness towards these two distinctly different mechanisms of propagation.

2) The normal flow of air in a real compressed-air conduit is of the order of a few cubic meters per second. Thus the explosion travels in a gas whose speed is of the order of 20 meters per second; the effectiveness of the anti-deflagration joints is thus diminished.

On the other hand, the effectiveness of the flame-cutter would definitely be increased by placing it as close as possible to the source of ignition, so that the combustion wave will not have attained too high a speed when it reaches the flame-cutter. In order that the flame-cutter operate effectively, it is evident that it must be located downstream of any possible source of ignition. However, it is probable that this source is located in the immediate vicinity of the compressor, and it would no doubt be possible to limit the distance between the flame-cutter and the compressor reservoir to approximately 10 meters. It is probable that, despite the reservations stated above, a flame-cutter similar to the one tested would have proven effective.

The inconveniences of a flame-cutter are obvious: other than its bulk (about one cubic meter), its weight (one ton), and its price, it causes an appreciable head loss. The flame-cutter which we tested had a useful cross section equal to the cross section of the conduit. Model tests led us to estimate the head loss at 100 g/cm^2, that is, one tenth of an atmosphere for a flow of 8 m^3/sec (measured at atmospheric pressure), which seems acceptable. However, we might be apprehensive that this head loss may increase rapidly, due to the fouling of the plates. The closer the flame-cutter to the compressor, the faster the plates foul.

V. CONCLUSION

The experimental data gathered during the course of this study may be summarized as follows.

1. There exist deposits, in compressed-air conduits, which consist essentially of oil, partially altered by oxidation, and to which are added mineral or combustible dusts and rust.

2. The oil deposit is oxidized by the action of a flow of hot air, thus creating combustible gaseous products; the reaction can be accelerated by certain catalysts, and notably, by rust. If the heat given off by the reaction is greater than that removed by conduction and convection, the temperature of the deposit may exceed that of the air flow and the reaction becomes a runaway.

The two essential factors which determine the development of the phenomenon are the temperature of the air and its speed. An increase of the former accelerates both the speed of reaction and the transfer of heat by convection. For a given air-flow temperature there exists a value of the speed at which the increase in temperature of the deposit is at a maximum; with our apparatus, this optimum value was of the order of a few centimeters per second.

3. By the play of the above reaction, a mixture of air and combustible vapor is established in the conduit, the concentration of which depends on the relative magnitude of the air flow on the one hand, and the speed of decomposition of the deposit on the other. When this concentration is within the limits of inflammability, the gaseous mixture ignites, either spontaneously or on contact with the deposit.

Once again, the two essential factors are the temperature and speed of the air or, more precisely, the law of the variation of the speed of the air as a function of time. A stoppage of the air flow for a short time is favorable for the ignition of the gaseous mixture. Under these conditions, and with our operating procedure, ignition was observed for an air-flow temperature between 147° and 157°.

4. For a compressor in service, operating at an average effective pressure of 5.5 kg/cm^2, the average temperature of the exhausted air maintained itself at 131° with peaks to 143°. These figures reached 145° and 153° respectively immediately preceding a revision of the installation.

At the time of restarts, which follow sub-atmospheric operation of short duration, the temperature of the air may exceed its normal level by 10° to 15° for a brief instant.

5. If we trigger the ignition of an inflammable gaseous mixture which is enclosed in a few meters of conduit whose inner surface is coated with an oil film a few tenths of a millimeter thick, an explosion is propagated along the entire length of the conduit. Its mechanical consequences are serious and consist, notably, of the rupture of the conduit at several points over the entire length.

Based on the experimental facts reported above, it is probable that the mechanism of the observed explosions is the following:

A fraction of the lubricating oil of the compressor is entrained by exhausted air in the form of fine droplets. These are deposited progressively on the walls of the reservoirs, nozzles, and conduits travelled by the air flow, thus impregnating the rust which has already been coated. The farther we are from the compressors, the less abundant this deposit becomes.

The air leaves the compressor at a relatively high temperature, a temperature which varies with the state of the installation and the pressure of the compressed air. Under normal operating conditions, the oil deposits are slowly oxidized, and this has no other consequence except the progressive alteration of the oil which forms them. If the temperature of the air is accidentally increased and if the air flow is sufficiently small but not nil, the oxidation reactions may "run away" and the deposit is raised to a high temperature. But if the combustible vapors produced by the decomposition of the deposit are diluted by an adequate air flow such that their concentration remains weak, the incident is limited to a simple "shot."

On the contrary, if the variations of air flow are such that at a certain moment and a certain point in the conduit, the concentration of combustible vapors reaches the ignition level, they are ignited and an explosion occurs. Notably, such a circumstance may be realized when the air flow is suddenly stopped while the oxidation reaction has already reached a more or less "runaway" condition. Obviously the explosion of the gaseous mixture is limited to the conduit section or reservoir which is filled with the inflammable gaseous mixture. By analogy with the terminology used in firedamp explosions, we call this explosion a "blaze." Its mechanical consequences are generally imperceptible.

However, if the formation of an inflammable gaseous mixture has succeeded in extending itself over a great enough length, for example, of the order of 10 to 15 meters, a blaze may start another type of explosion which is directly fed by the oil deposit and is capable of high-speed propagation of the order of one kilometer per second, and for as long a time as it meets with a sufficiently abundant deposit of oil.

Thus we will observe either a blaze or a general explosion, depending on the importance of the volume of inflammable gaseous mixture generated by the local decomposition of the oil coating. It seems that exceptional circumstances would be necessary for this volume to attain a serious level, as it is quite probable that the gaseous mixture would be ignited as soon as it reached the ignition level. Chances are very slim that the latter level would be reached at the same time throughout an appreciable length of conduit. To be sure, this is the reason why explosions of the "blaze" type are frequently observed and also why general explosions are extremely rare.

It behooves us not to draw practical consequences from this study. We will limit ourselves to the following statement. In order to prevent explosions in compressed air conduits, we may consider several solutions:

--preventing the formation of an oil deposit in the conduits;

--limiting the temperature of the compressed air as it enters the conduits or, finally;

--inserting an apparatus which is capable of stopping an explosion which is already underway.

Only a very thin deposit is needed to permit the propagation of an explosion. Thus it is doubtful whether an effective filtration of the air can be permanently assured without very onerous practical constraints.

In order that flame-cutting apparatuses be effective, they must be large; thus they are cumbersome. Moreover, they oppose the consequences of a general explosion and not those of a blaze.

Thus it seems that the best solution is to limit the temperature of the compressed air. We can, for this purpose:

--either install a refrigerant downstream of the high-pressure exhaust (this is the radical solution, but obviously a burdensome one);

--or limit ourselves to placing a thermostat on the exhaust conduit to stop the equipment as soon as the temperature reaches a certain level. In the choice of this value, it behooves us to remember that the figures of this report which were indicated as having triggered either a burning of the oil coating or an ignition of oil vapors are valid, in a strict sense, only for the operating procedure in question.

VI. FIGURE APPENDIX

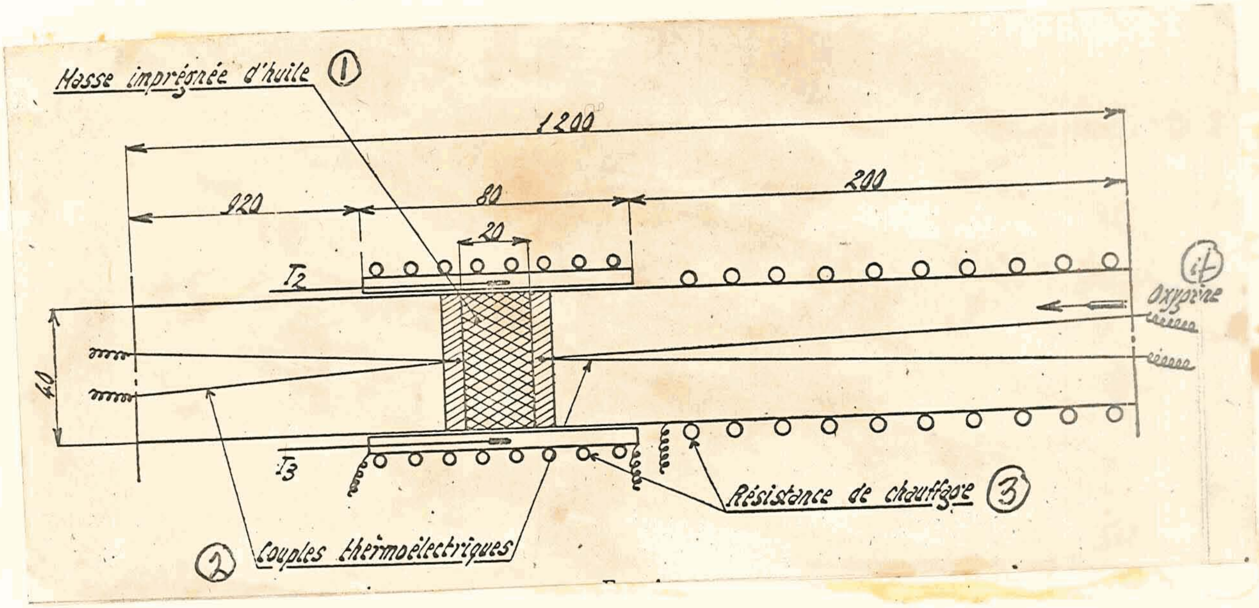


Figure 1.

Legend: 1--Oil-impregnated mass; 2--Electric thermocouples; 3--Resistance heater; 4--Oxygen.

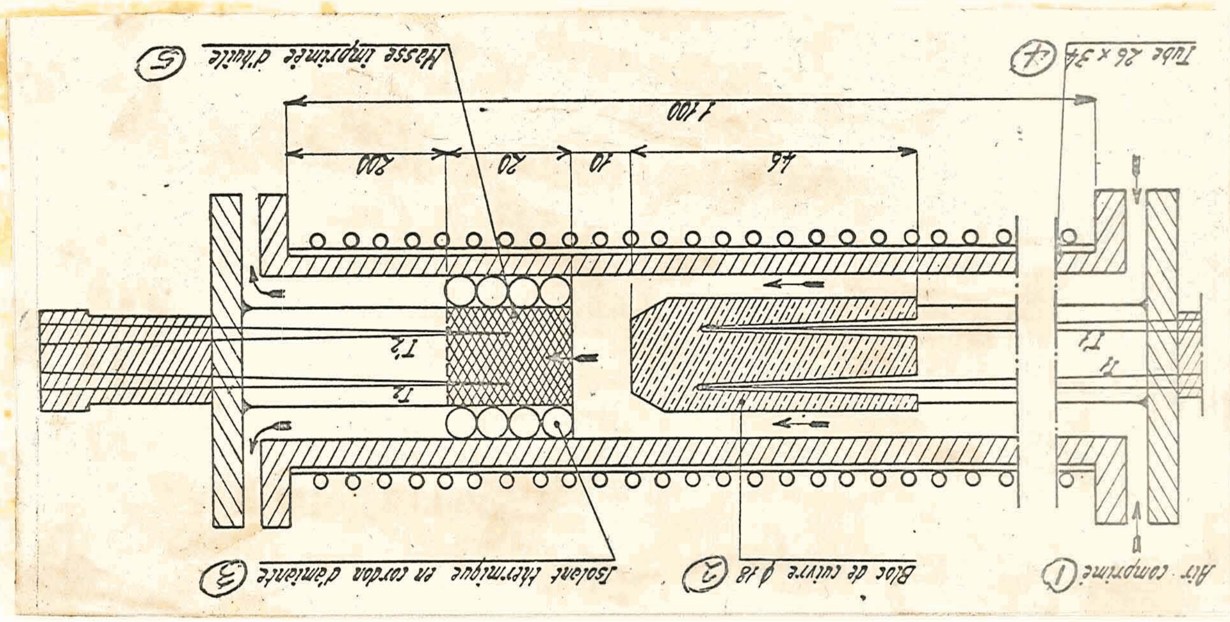


Figure 2.

Legend: 1--Compressed air; 2--Copper block, diam 18 mm; 3--Asbestos rope thermal insulation; 4--Pipe 26 x 34; 5--Oil-impregnated mass.

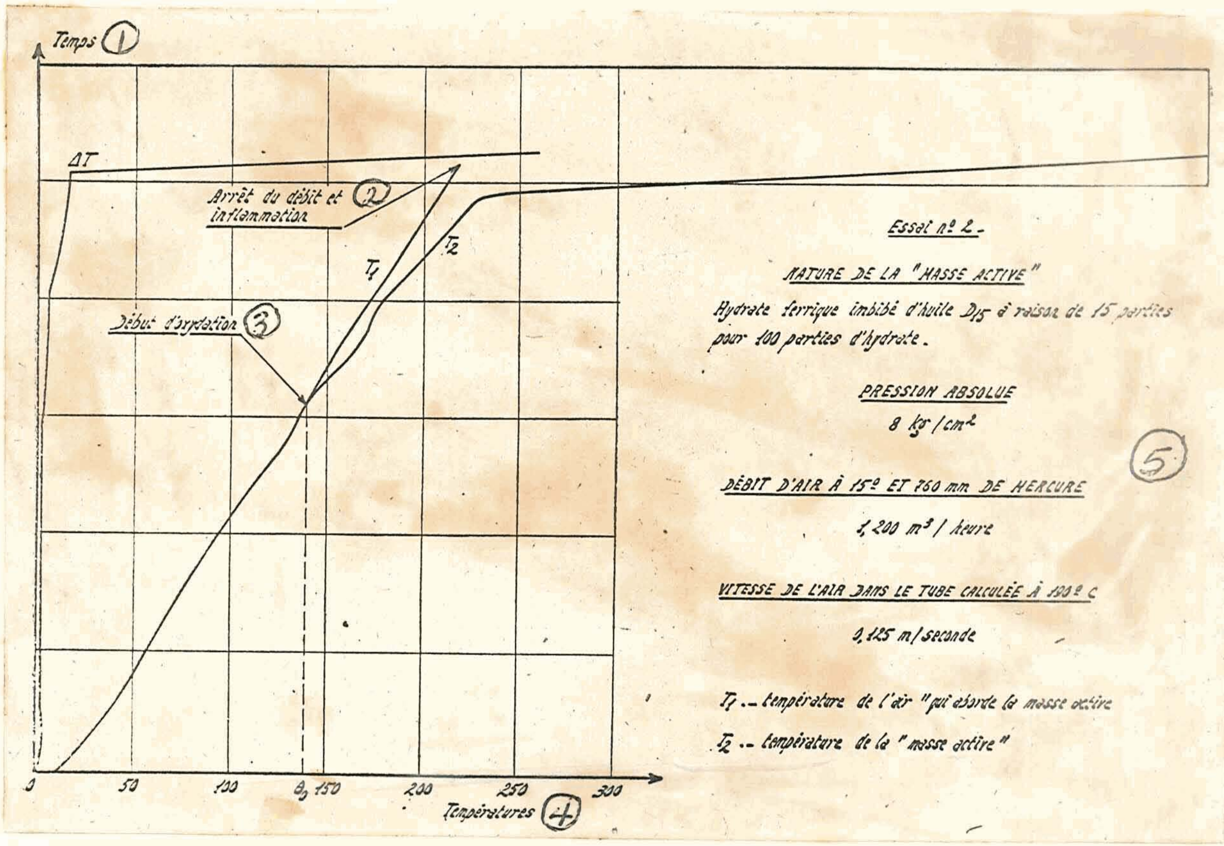


Figure 3.

Legend: 1--Time; 2--End of flow and ignition; 3--Start of oxidation; 4--Temperatures; 5-- Test No. 2

Nature of the "Active Mass"

Ferric hydrate impregnated with 15 parts of D 15 oil to 100 parts of hydrate

Absolute pressure

8 kg/cm^2

Air Flow at 15° and 760 mm of mercury

1,200 m^3/hr

Air velocity in the tube calculated at 190° C

0.125 m/sec

T_1--temperature of the air next to the active mass

T_2--temperature of the "active mass."

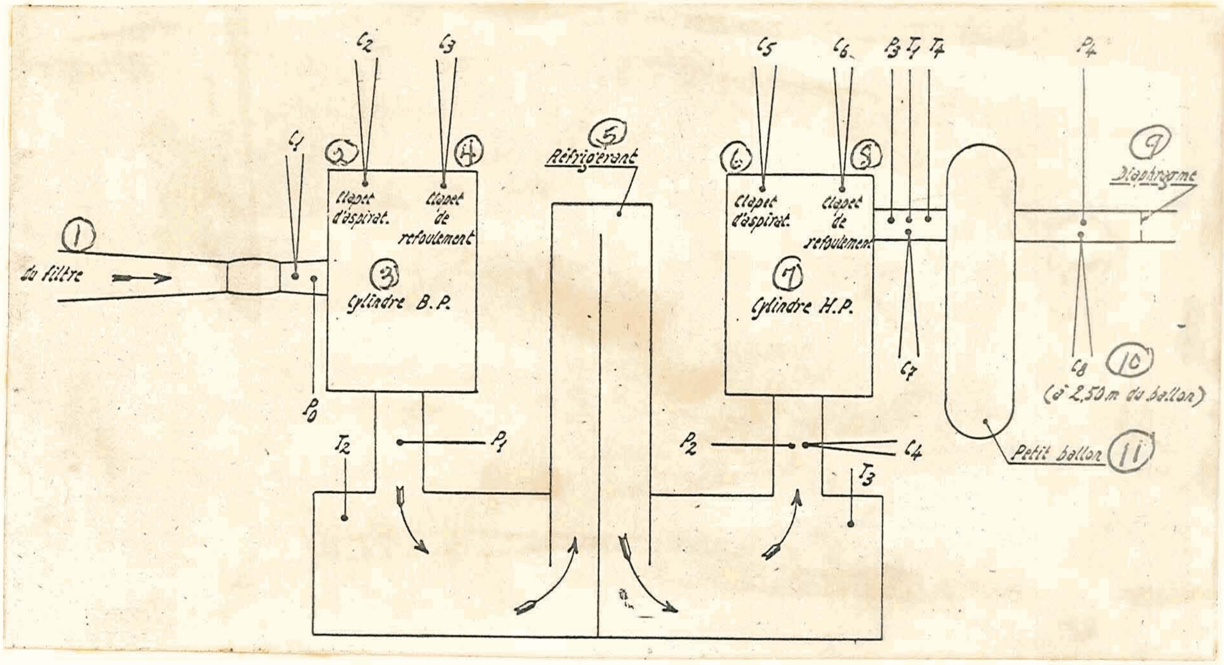


Figure 4.

Legend: 1--From filter; 2--Intake valve; 3--Low-pressure cylinder; 4--Exhaust valve; 5--Refrigerant; 6--Intake valve; 7--High-pressure cylinder; 8--Exhaust valve; 9--Diaphragm; 10--(2.5 m from flask); 11--Small flask.

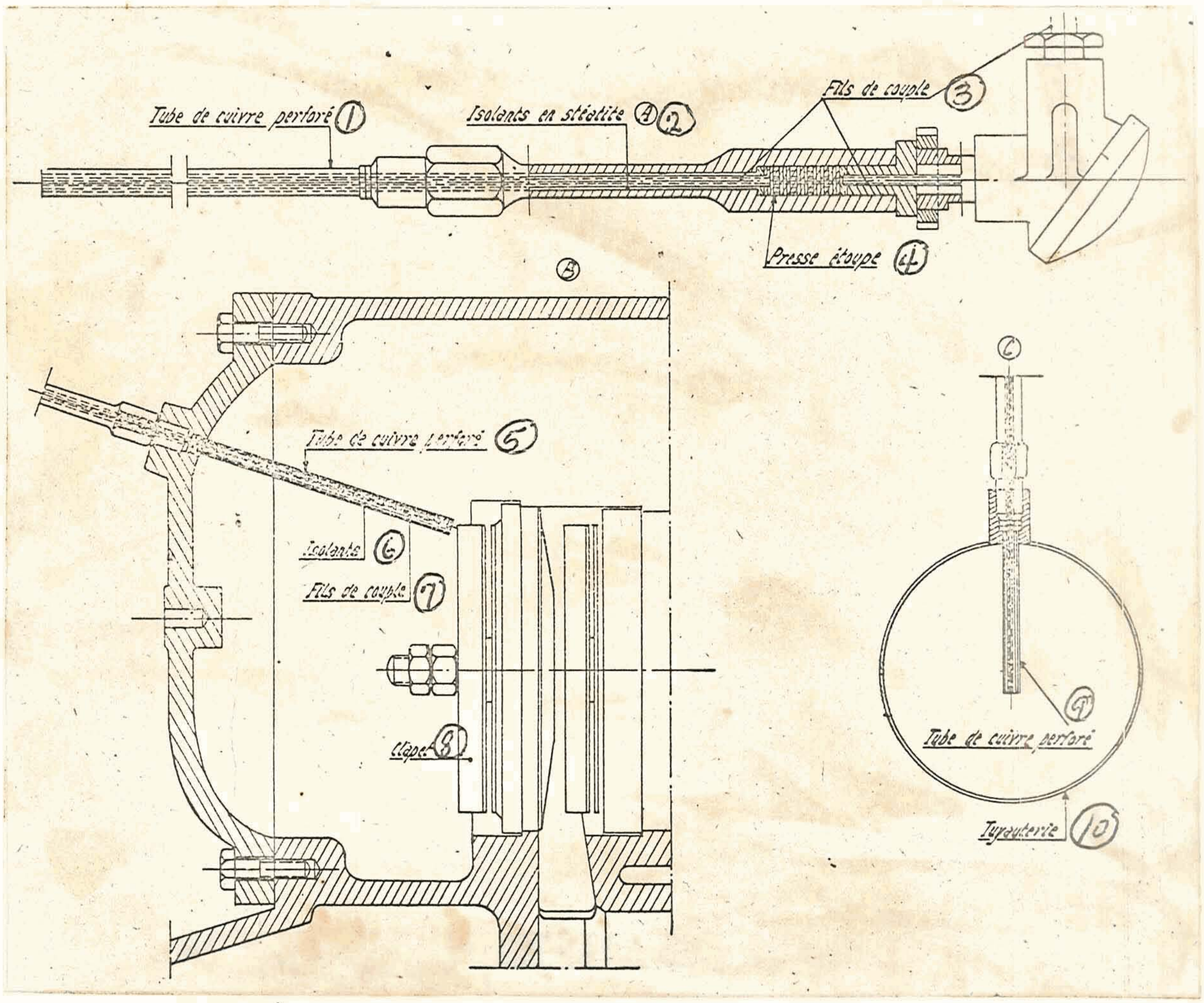


Figure 5.

Legend: 1--Perforated copper tube; 2--Steatite insulation; 3--Couple leads; 4--Sealing caulking; 5--Perforated copper tube; 6--Insulation; 7--Couple leads; 8--Valve; 9--Perforated copper tube; 10--Piping.

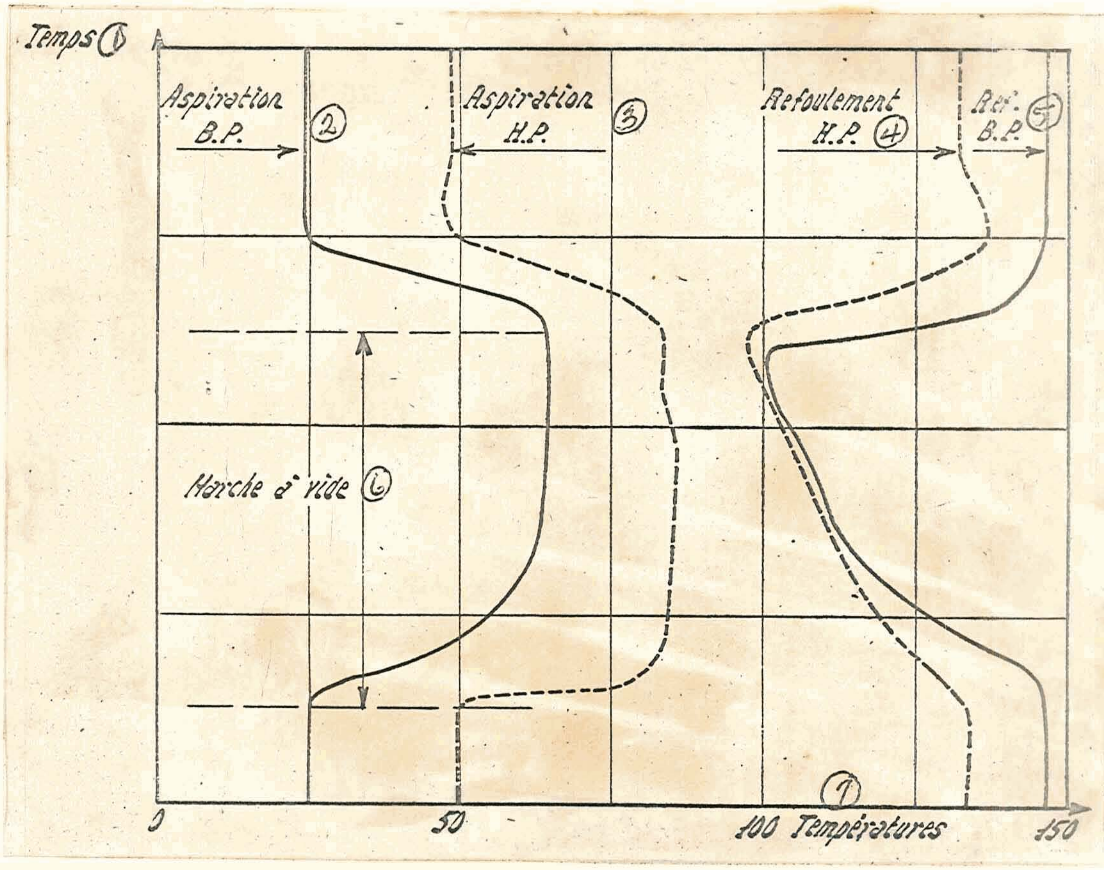


Figure 6.

Legend: 1--Time; 2--Low-pressure intake; 3--High-pressure intake; 4--High-pressure exhaust; 5--Low-pressure exhaust; 6--Vacuum operating conditions; 7--Temperature.

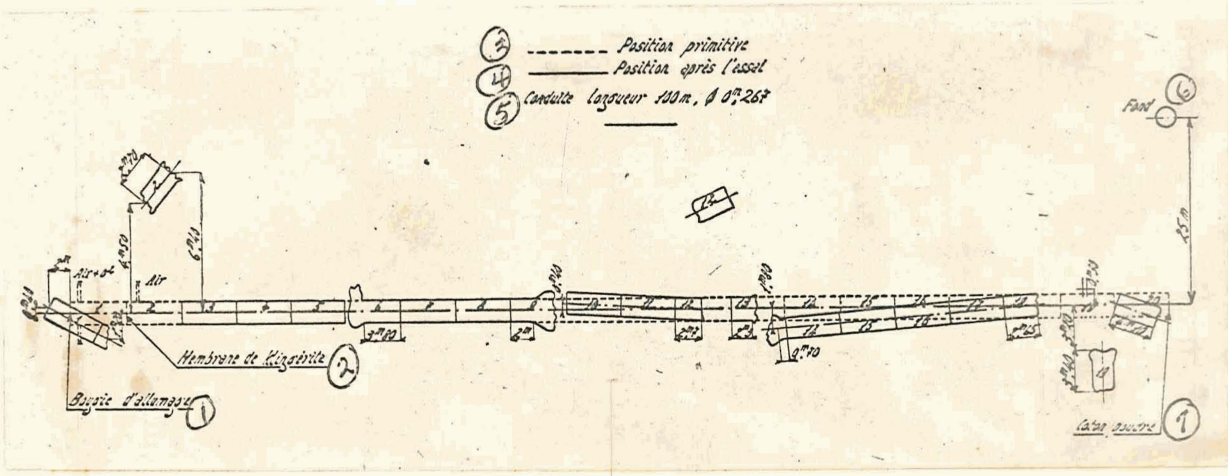
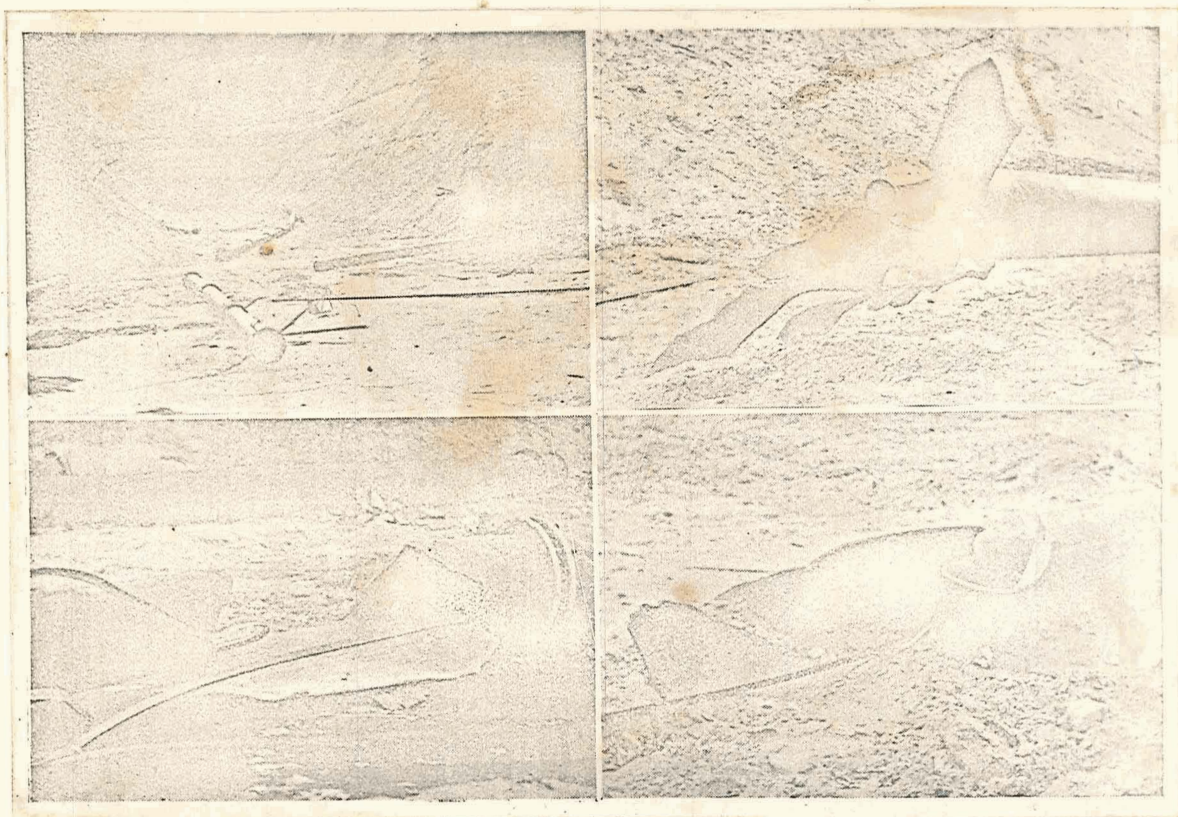


Figure 7.

Legend: 1—Ignition spark plug; 2—Klingerite membrane; 3—Original location; 4—Location after test; 5—Length of conduit; 6—Bottom; 7—Cotton powder.



Figures 8, 9, 10, 11.

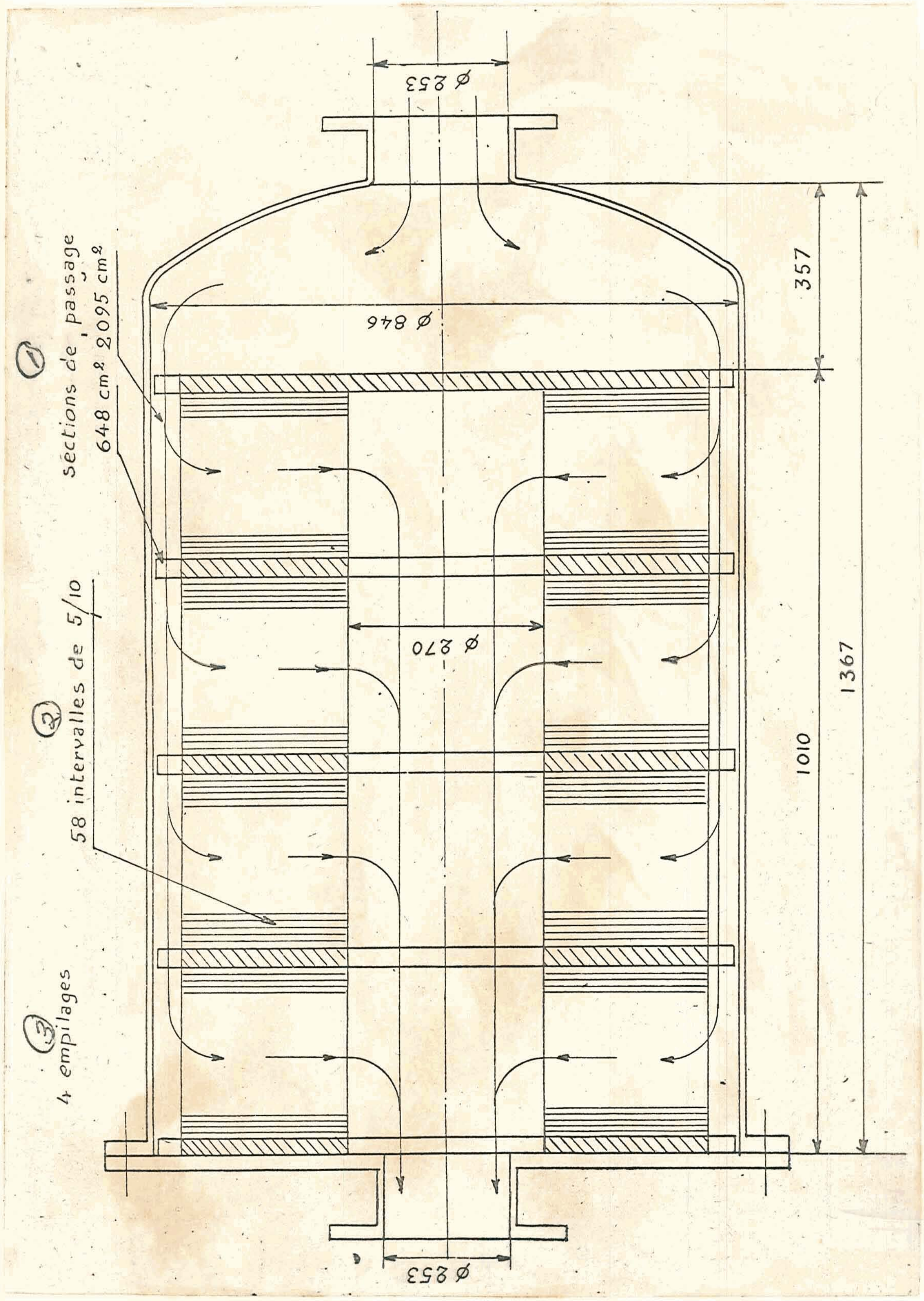


Figure 12. Legend: 1—Passage cross sections; 2—58 Intervals; 3—4 Stacks.

- END -